

# Spalling of Concrete: Implications for Structural Performance in Fire

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**ABSTRACT:** This preliminary paper is a progress report on an analytical investigation into the implications of explosive spalling on the fire performance of reinforced concrete structural elements and whole structures. This study does not attempt to predict whether spalling will occur. For accurate prediction of the occurrence of spalling a complete and fully coupled hygro-thermal-mechanical (HTM) analysis is required, as described by a comprehensive review of current research into the parameters and mechanisms that influence spalling, including a review of physical spalling criteria. This paper describes the structural performance of spalled concrete elements, using finite element analysis where spalling is modelled by removing layers of concrete when a set of spalling criteria are met. The method is presented using a case study of a simply supported reinforced concrete beam, where the analytical results indicate that spalling invariably triggers an early failure (well short of the required FRR rating) of a beam exposed to the standard fire.

## 1 INTRODUCTION

While concrete structures have exhibited good performance in fire they have also exhibited disproportionate levels of damage and complete collapse (Buchanan 2001, Beitel & Iwankiw 2002). Such occurrences highlight the shortfalls in our understanding of the mechanisms of concrete performance in fire, in both the research and commercial design fields.

Spalling involves the breaking off of layers or pieces of concrete from the surface during thermal exposure. Spalling can broadly be classified into 3 different types: aggregate spalling, corner spalling (or sloughing off) and explosive spalling. Aggregate spalling is caused by aggregate failure close to the surface and involves small pieces flying off from the surface. This type of spalling does not adversely affect the structural performance, causing only superficial damage.

Corner spalling occurs later, often in the decay stages of the fire. It is characterised by larger corner pieces falling off the concrete due to tensile cracks developing at corners and edges. Due to the late onset of this type of spalling the concrete affected is already considerably weakened from fire exposure and any exposed reinforcement is subjected to much lower temperatures. Thus corner spalling is not thought to have a significant impact on structural fire performance.

Explosive spalling involves the ejection of pieces of concrete from the heated surface at high veloci-

ties. It typically occurs in the early stages of the fire when heating rates are high (Khoury 2000, Hertz 2003). Explosive spalling (hereafter referred to as spalling for brevity) poses the greater threat to structural stability; it is therefore the form of spalling focused upon in this paper.

Current research is predominantly concerned with establishing and modelling the precipitating mechanisms. Prediction of spalling requires hygro-thermal-mechanical modelling; the reliability and accuracy of such models however is not yet sufficient to formulate design guidelines, hence there is little guidance provided under BS 8110 part 2 (BSI 2004) and the new Eurocode 2 (EC2 1996) with regards to protection of concrete structures in the event of spalling.

In this paper, the current limitations in our understanding and design guidance under EC2 for spalling of concrete structures are discussed. In addition a preliminary investigation on the effect of spalling on structural stability is performed through finite element analyses of a reinforced concrete beam subjected to the Eurocode 1 (EC1 2002) standard temperature – time curve.

## 2 DESIGN FOR SPALLING

Currently, design guidance for the protection of structures against spalling is patchy. In EC2 no checks for spalling are required from the designer if:

- The moisture content of the member is less than 3% or the member is designed for internal exposure
- The tabulated data is used to prescribe generic fire ratings for concrete elements (except for axis distances  $> 70$  mm)

However, if the designer expects the moisture content to be greater than 3% for beams, slabs and tensile members the effect of spalling on the load bearing function of the element is checked by assuming local loss of cover to one reinforcing bar or bundle of bars and calculating the reduced load bearing capacity. This check is not deemed necessary where the number of bars is high enough, it is assumed that an acceptable level of redistribution of stress is possible without loss of stability. Examples given of where the number of bars is high enough to allow redistribution of stress are: solid slabs with evenly distributed bars and beams of widths greater than 400 mm and 8 bars in the tensile region.

Concrete structures are generally designed for fire using the tabulated data thus it is apparent that there are very few occasions when a designer must consider the possible effects of spalling on structural stability. If checks must be made they are then limited to only considering localised spalling.

The tabulated data is compiled from the results of standard fire resistance tests of isolated elements, generally without any spalling having occurred. Therefore continued reliance on this empirical data to account for the possible debilitating effects of spalling masks the mechanisms of how an element or a whole structure truly performs in the event of spalling. Potential alternative load paths or stability mechanisms such as compressive membrane action are ignored.

### 3 MECHANISMS OF SPALLING

Spalling of concrete is generally categorised as pore pressure induced spalling, thermal stress induced spalling or a combination of the two.

#### 3.1 *Pore pressure induced spalling*

As concrete is heated the free water vaporises at  $100^{\circ}\text{C}$  and expands; thereby resulting in increased pore pressures. Migration of some this vapour to the interior of the concrete member, where it cools and condenses, will result in an increasingly 'wet' zone (sometimes referred to as moisture clog). At some distance from the hot surface the vapour front reaches a critical point at which a maximum pore pressure is achieved (further movement will result in a reduction in pressure). The distance of this point from the heated surface will depend on the con-

crete's permeability. Pore pressure spalling occurs if the maximum pore pressure is greater than the local tensile strength of the concrete. However, no pore pressures have yet been measured which would exceed the tensile strength of concrete which suggests that pore pressure in isolation does not lead to the occurrence of spalling (Khoury & Anderberg 2000, Jansson & Bostrom 2008).

#### 3.2 *Thermal stress induced spalling*

Strong thermal gradients develop in concrete as it is heated, due to its low thermal conductivity and high specific heat. These thermal gradients induce compressive stresses close to the surface due to restrained thermal expansion and tensile stresses in the cooler interior regions. The surface compression may also be augmented by applied loading or prestress.

#### 3.3 *Combined pore pressure and thermal stress induced spalling*

It is most likely that spalling occurs due to the combination of tensile stresses induced by thermal expansion and increased pore pressure. Much debate still surrounds the identification of the key mechanism (pore pressure or thermal stress) (Khoury & Anderberg 2000). However, it is noted that the key mechanism may change depending upon the section size, material and moisture content (Davie et al. 2008).

## 4 SPALLING MODEL

### 4.1 *Spalling Criteria*

From the previous discussion of the governing mechanisms of spalling it is evident that the stress state within the concrete will dictate whether spalling will occur. The stress state due to moisture migration and thermal stress will be influenced by several parameters.

Material parameters that contribute to the occurrence of spalling include: initial moisture content, concrete permeability, porosity and the presence of cracks, aggregate type, aggregate size and amount of reinforcement. Geometric factors include section shape and size. Environmental factors include heating rate and profile, temperature level and thermal restraint (Khoury 2000, Hertz 2003).

It is not the intention of this investigation to model explicitly the hygro-thermal-mechanical processes which determine this stress state. There is a

large body of research which has sought to characterise the conditions under which spalling occurs. A comprehensive review of this research has been undertaken to identify critical conditions or parameters for spalling which are usable within a structural analysis. The fundamental assumption in this analysis is that spalling *will* occur, thus it assumed that the material and geometric conditions which trigger spalling are satisfied.

Assuming that spalling will occur, it is then necessary to define *when* spalling will occur during fire exposure. The environmental parameters of heating rate and temperature level are useful indicators in a thermal analysis of when spalling may occur. From the literature it is found that heating rates in the range of 20 – 32°C/min are significant for spalling (Khoury 2000). Such high heating rates normally occur in the early stages of the fire which is consistent with the experimental observations. Several researchers have identified critical temperature ranges for the exposed surface at the onset of spalling. Akbaruzzaman and Sullivan (1970) have cited exposed surface temperatures in the range of 375–425°C for normal weight concretes.

#### 4.2 Spalling Implementation

A 2-D heat transfer analysis of the member cross section is performed using ABAQUS finite element software (ABAQUS 2006). The onset of spalling is triggered when the bottom surface temperature reaches the range of 375–425°C. Spalling is modelled by removing all the elements making up the bottom concrete cover. The analysis is continued and the temperature distribution for the reduced cross section is calculated.

Removing all of the concrete cover instantaneously when the bottom surface reaches a certain temperature greatly simplifies the progressive nature of spalling. Slower and more progressive spalling can also be modelled by employing the same temperature criteria but only removing single layers of elements at time. The thickness of the layers removed will be a function of the element thickness used in the finite element analysis.

### 5 CASE STUDY

The performance of a simply supported RC beam exposed to the EC1 standard temperature-time curve (Figure 1) and subject to spalling is investigated.

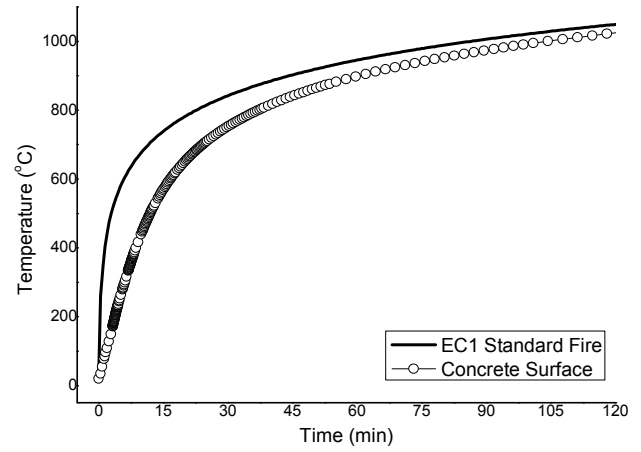


Figure 1. Eurocode 1 standard temperature curve and concrete surface temperature.

The beam is 600 mm deep, 300 mm wide and 6000 mm long. The concrete strength  $f_{cu}$  is assumed to be 30 MPa. The beam is reinforced with six 16 mm steel bars of yield strength,  $f_y = 500$  MPa. The cover depth is assumed to be 45 mm. Temperature dependant material properties for both the concrete and reinforcing steel are taken from Eurocode 2.

The load ratio is defined as per Equation 1 below:

$$r_{load} = M^*_{fire} / R_{cold} \quad (1)$$

where  $M^*_{fire}$  = Applied bending moment in fire conditions and  $R_{cold}$  = Ambient ultimate capacity. For an applied load of 34 kN/m during the fire the beam has a load ratio,  $r_{load} = 0.5$ .

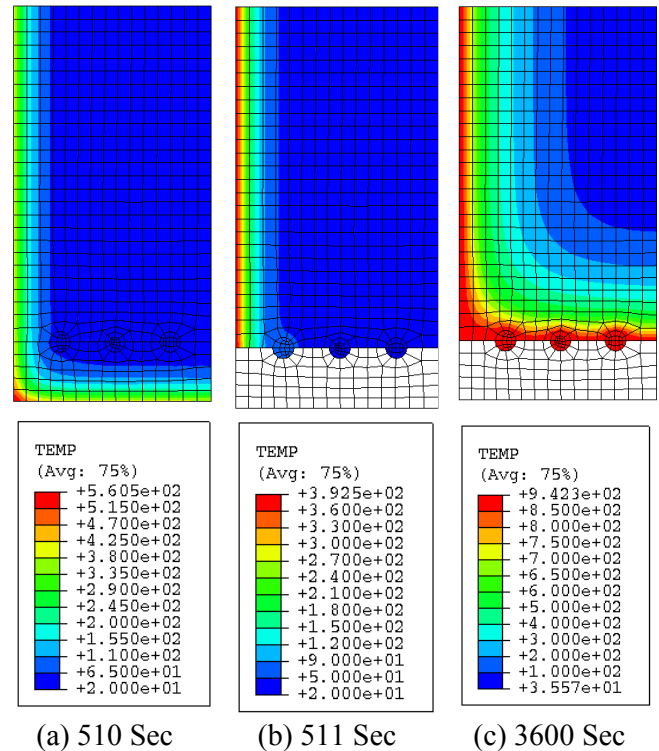


Figure 2. Temperature profile (°C) through the beam cross section at different times for abrupt spalling case

Symmetry is taken advantage of and half of the beam cross section is analysed for the case of no spalling, progressive spalling (8 mm layers) and abrupt spalling. The rapid evolution of concrete surface temperature in Figure 1 would indicate that varying the criterion temperature between 375°C to 425°C would have little effect on the final temperature distribution therefore the surface temperature criterion for the onset of spalling is taken as a single value of 400°C.

Figure 2 presents the temperature contour plots just prior to and just after spalling and one hour from the beginning of the analysis for the abrupt spalling analysis.

For each case the resulting evolution of temperature in the reinforcement is plotted in Figure 3 (a). The corresponding reduction in yield strength is plotted according to the reduction factors provided in Eurocode 2 is plotted in Figure 3 (b).

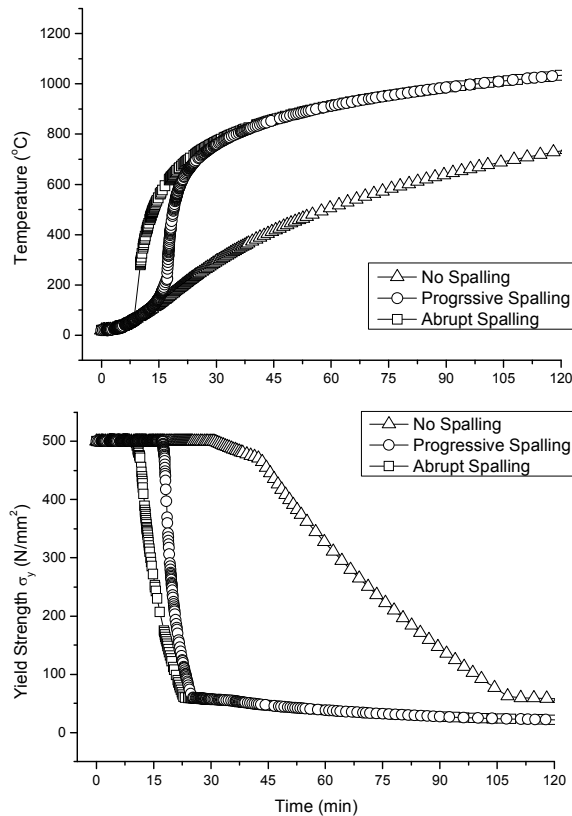


Figure 3. (a) Temperature development and (b) reduction in yield stress in reinforcing steel on exposure to the standard fire.

## 6 DISCUSSION

For the case of no spalling the steel temperatures rise gradually, being insulated by the concrete cover. The surface temperature reaches 400°C after 9 minutes of exposure. Removal of the concrete cover instantly results in a sharp increase in steel temperatures and a corresponding reduction in steel strength. Modelling spalling in a progressive manner with the same spalling criteria delays the sharp rise in steel tem-

perature from 9 minutes to 17 minutes from the start of exposure.

The sharp increase in temperature clearly equates to a sharp decrease in the capacity of the steel member so we can predict the likely failure time of the simply supported beam based on the steel temperatures.

The beam has a load ratio of 0.5. Thus when the steel strength falls to 50% of its ambient value the ultimate moment capacity is exceeded and the beam will fail if the spalling occurs at the location of maximum moment. The failure time for each scenario is presented in Table 1. It is apparent that spalling significantly reduces the failure time of the simply supported concrete beam when exposed to the standard fire. Note that the failure time predicted with spalling (even in progressive spalling) is well short of the time when the cooling phase typically starts in 'natural' or parametric fires (EC1 2002). Hence it can be argued that consideration of the cooling phase will not alter the prediction of failure time.

Table 1. Failure times for simply supported beam for a load ratio of 0.5

Case	Failure Time
	min
No spalling	72
Progressive spalling	20
Abrupt spalling	15

In this analysis the standard temperature-time curve has been used to define the thermal exposure for the beam, assuming uniform thermal exposure along the length and across the width of the beam. Therefore a thermal criterion for the onset of spalling in conjunction with the standard temperature-time curve predicts that spalling will also occur uniformly over the full length and width of the bottom surface of the beam. In reality this is not the case, because spalling may be localised to regions of high thermal exposure.

The failure times calculated in Table 1 are based on spalling occurring at the location of maximum moment. If spalling occurs away from the location of maximum moment it may be assumed that failure times will increase as the demand on the steel is less. However, from Figure 3 (b) it can be seen that the reduction in steel yield strength after spalling is rapid. For the case of abrupt spalling it takes 6 minutes from the beginning of spalling until the steel has reached 50% ambient capacity. It takes just a further 5 minutes to reach 10% of the steel's capacity. Therefore we can conclude for this case study that localised spalling will vary the failure time but not significantly.

This conclusion is only valid for a simply supported member where there is no opportunity for

moment redistribution or additional load carrying capacity from axial restraint. The effects of localised spalling become more complicated in the case of a continuous multi-span beam such as that in Figure 4 or a slab.

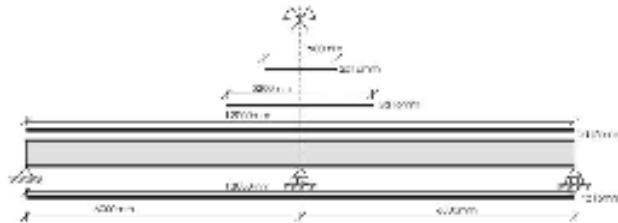


Figure 4. Two span RC beam

In a multi-span beam or slab failure at one location will not necessarily result in overall failure of the beam due to the moment redistribution that can occur through continuity. Determination of failure becomes more complicated due to this continuity also. Not only is the tensile steel within the span affected but also the beam underside in compression at the continuous support. Fire exposure of this region reduces the compressive capacity of the beam and spalling will potentially exacerbate this through the loss of cross section. The hogging reinforcement in the top of the beam will however remain largely unaffected.

Previous research (Bernhart et al. 2005) has looked at many parameters that affect the performance of multi-span beams in fire such as reinforcement ratio and support conditions; it has not however considered the implications spalling will have for performance.

## 7 CONCLUSIONS

Explosive spalling is a very complex phenomenon which poses a great threat to structural performance of some reinforced concrete structures in fire. There is a large body of research concerning the prediction of whether spalling will occur, but rather less research concerning the implications that spalling has for structural performance. Current design guidance for the consideration of spalling is limited thus spalling is largely ignored in the design process of concrete structures despite its potential consequences.

The results of the analysis of a simply supported beam indicate that spalling threatens stability of the structure by exposure of the reinforcement to high and rapidly rising temperatures. It is shown that under exposure to the standard fire, failure times are significantly reduced for both models of spalling (abrupt and progressive spalling).

The effect of localisation on failure times for a simply supported beam is not significant due to the rapid decline in steel capacity after spalling has occurred. For multi-span beams the effect is more complicated. In the future the study will be extended to consider localised spalling implications in combination with a non-uniform heating definition for multi-span beams and slabs.

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